# The Future of Silicon Solar Cells

Eicke R. Weber

*Fraunhofer-Institute for Solar Energy Systems ISE*

*and*

*Albert-Ludwigs University Freiburg*



Fraunhofer ISE

ALBERT-LUDWIGS-UNIVERSITÄT FREIBURG

# Fraunhofer-Institute for Solar Energy Systems ISE

Largest european solar energy research institute

830 members of staff (incl. students)

10% basic financing
90% contract research
40% industry, 60% public
€ 52.4 M total budget (‘08)
> 10% p.a. growth rate

Areas of business:

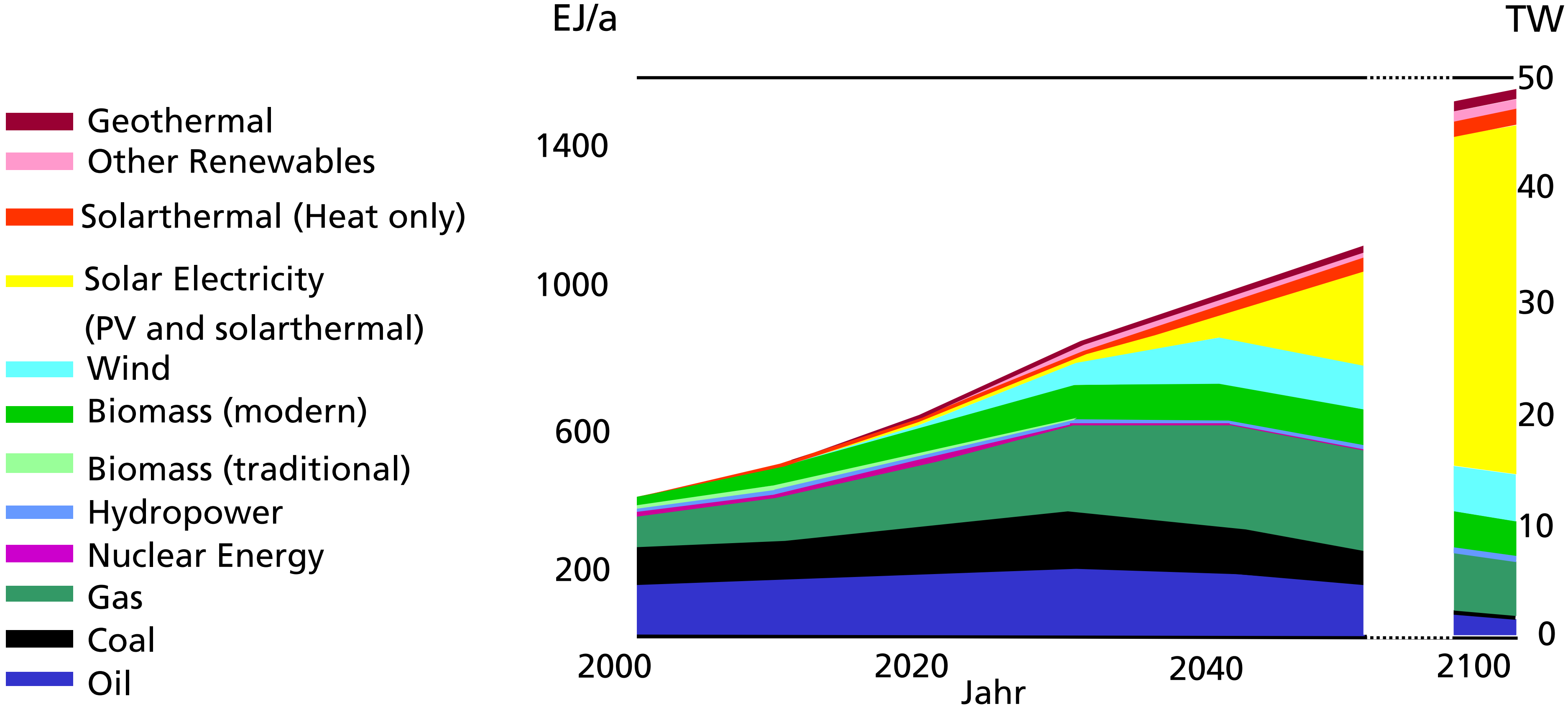
- Photovoltaics
- Solar Thermal Technologies
- Renewable Power Generation
- Energy-Efficient Buildings and Technical Building Components
- Applied Optics and Functional Surfaces
- Hydrogen Technology

# Magnitude of Solar Energy

- Each hour the sun delivers to earth the amount of energy used by humans in a whole year
- Sun radiation onto earth corresponds to 120,000 TW
- Total human energy need in 2020: 20TW!

Source: G.W. Crabtree and N.S. Lewis, Physics Today, March 2007

# Exemplary Path, global primary energy consumption




Source: Scientific Council of the German Federal Government on Global Environment Change, 2003, www.wbgu.de

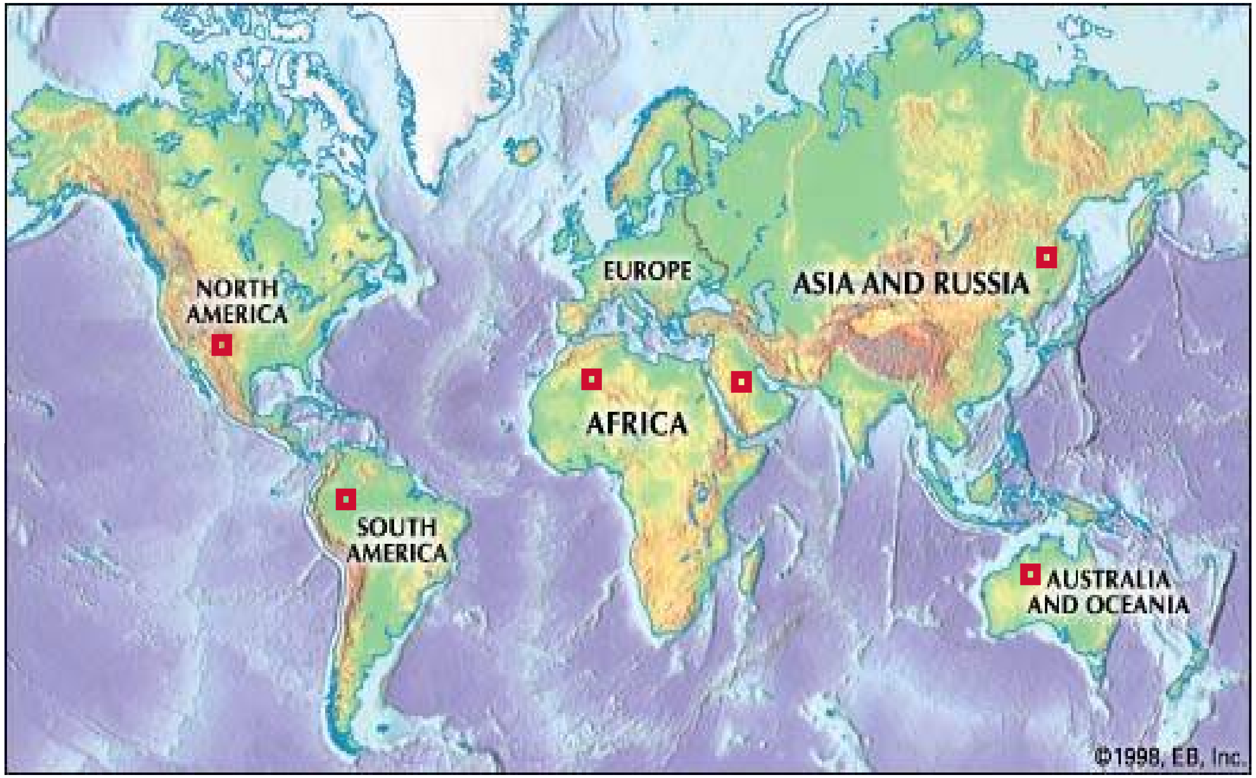
# Required Area for PV

Area required to produce 20 TW through PV:

6 sites, 340 x 340 km$^2$ each producing 3.3 TW

*(using 15% PV cells, 1600hrs/a of sunshine)*

**PV can easily supply a substantial part of the world energy needs**



Solar energy

is the only kind of energy that can solve the earth's energy problems!

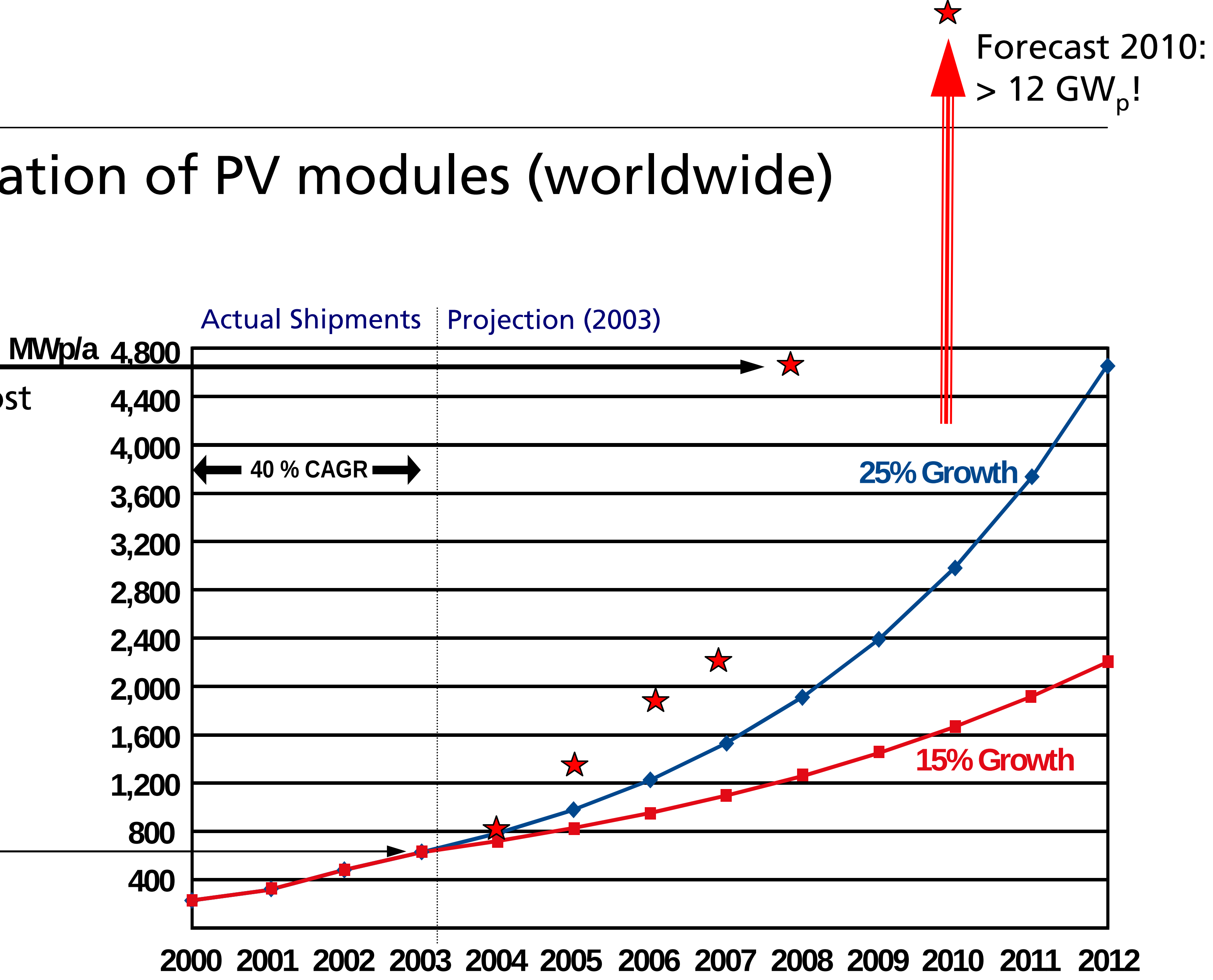
Forecast 2010: > 12 $GW_p$!

# Annual installation of PV modules (worldwide)

2008: above 4.5 $GW_p$

again, far above the most optimistic forecast!

2003: 600 $MW_p$

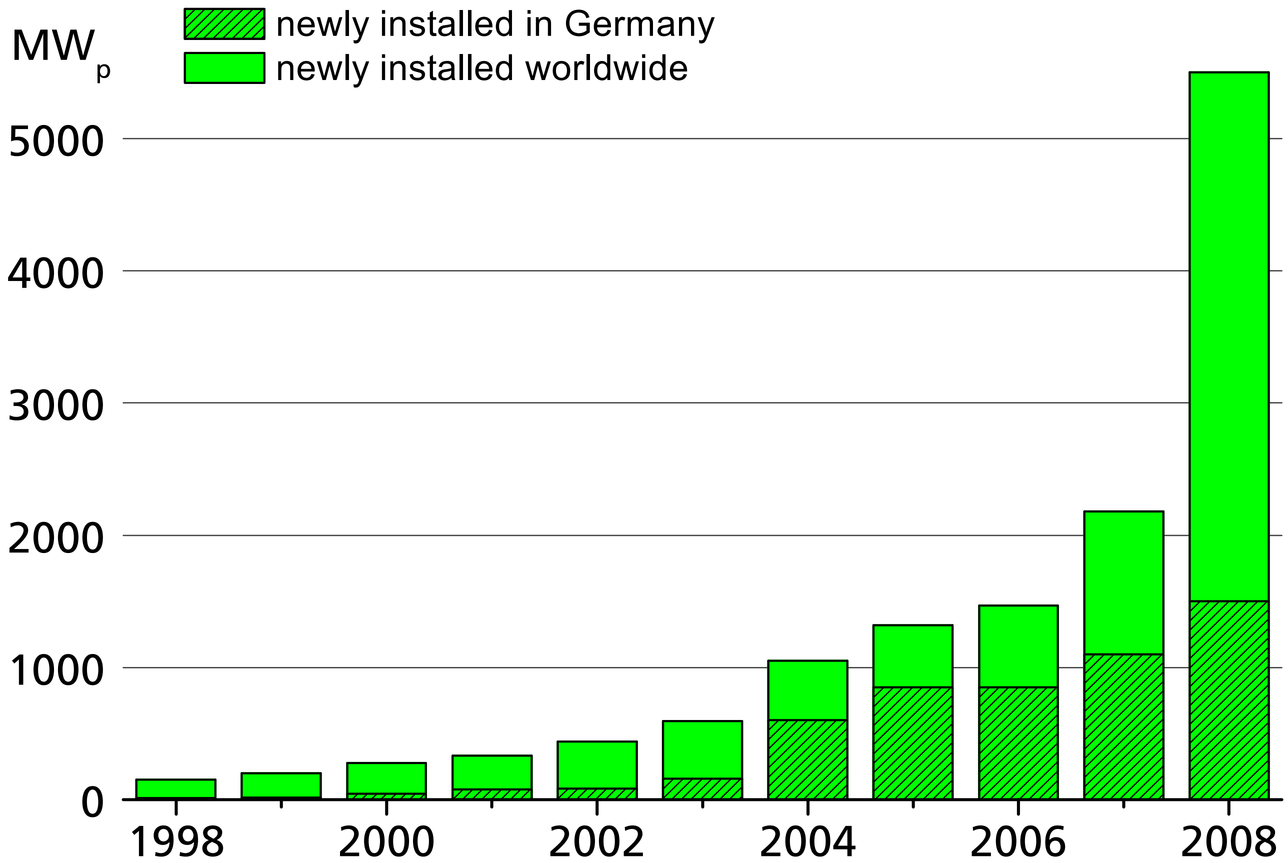



Source: 2000-2003 Strategies Unlimited, EPIA "solar generation" 2006, 2010 Rogol, LBBW Report 2007



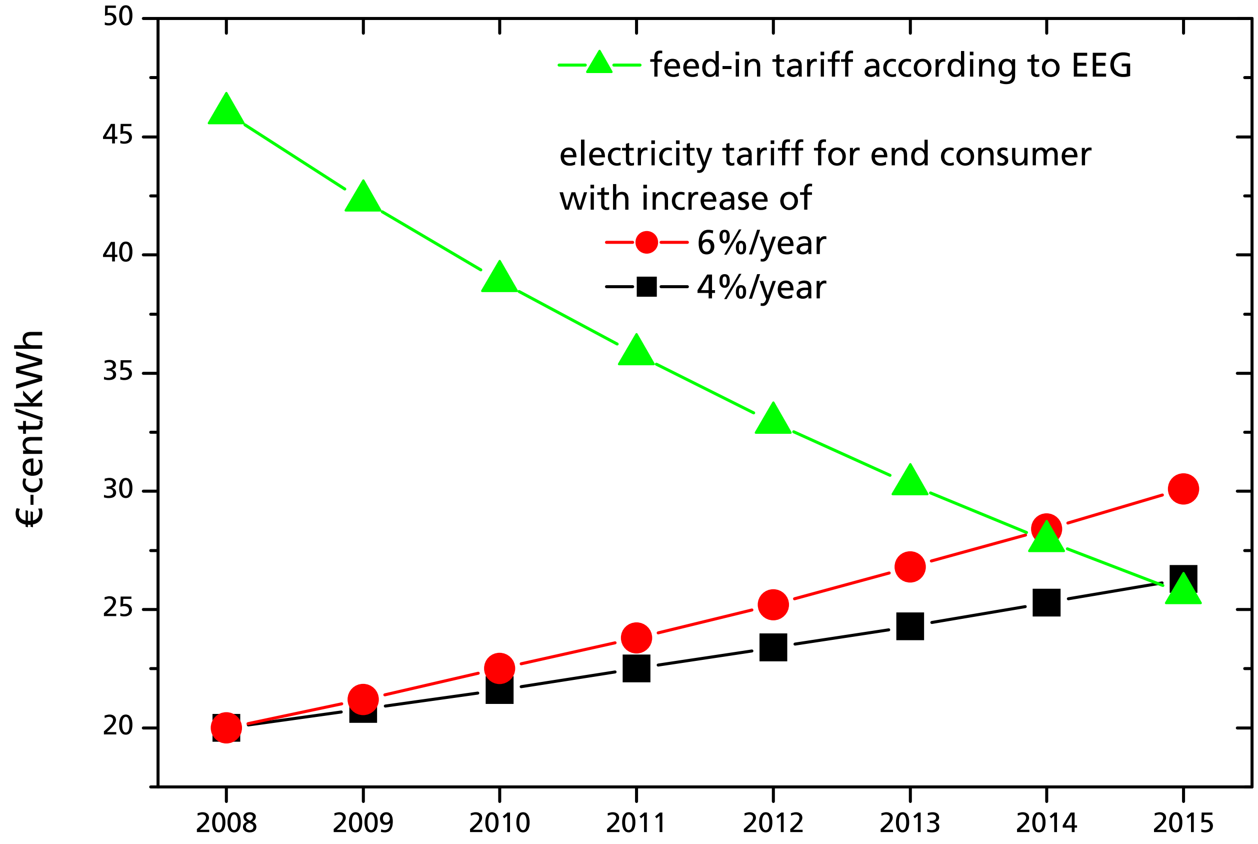
Fraunhofer ISE

# Global PV-Installations

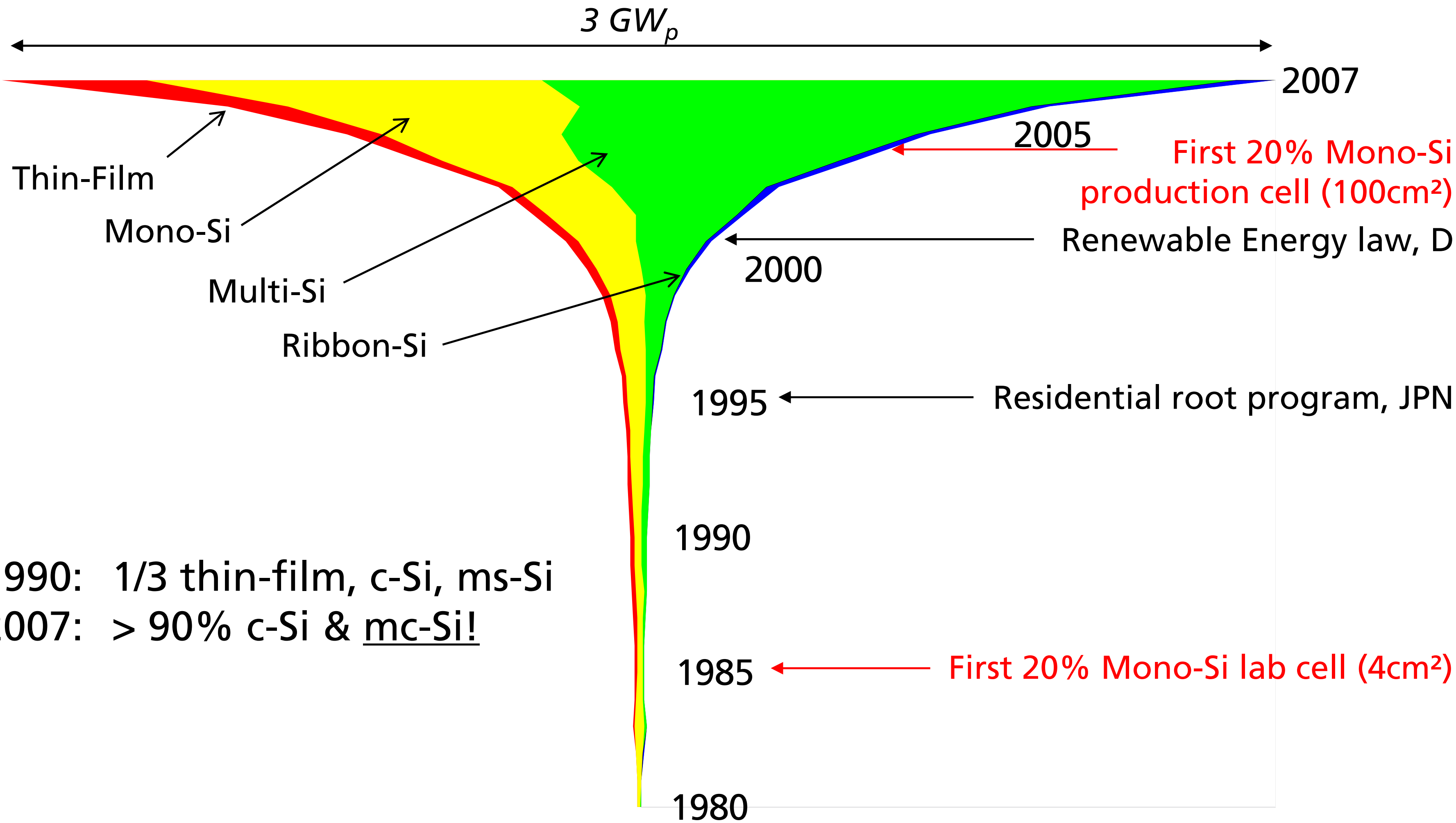



Source: EPIA, BSW

# Path to Grid Parity in Germany (!)



# Development of the global PV-market

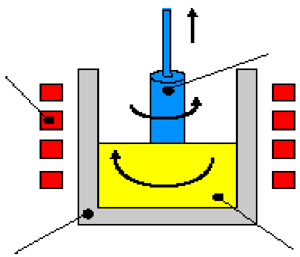



1990: 1/3 thin-film, c-Si, ms-Si
2007: > 90% c-Si & <u>mc-Si!</u>

# Two technologies currently dominate the PV market

**Single Crystals:**
- highest efficiency
- slow process
- high costs

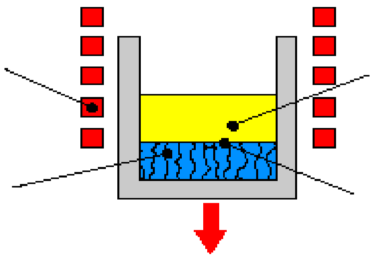
Pulling of Single Crystals (Czochralski)



QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

**Multi crystalline (mc):**
- low cost
- fast process
- lower efficiency

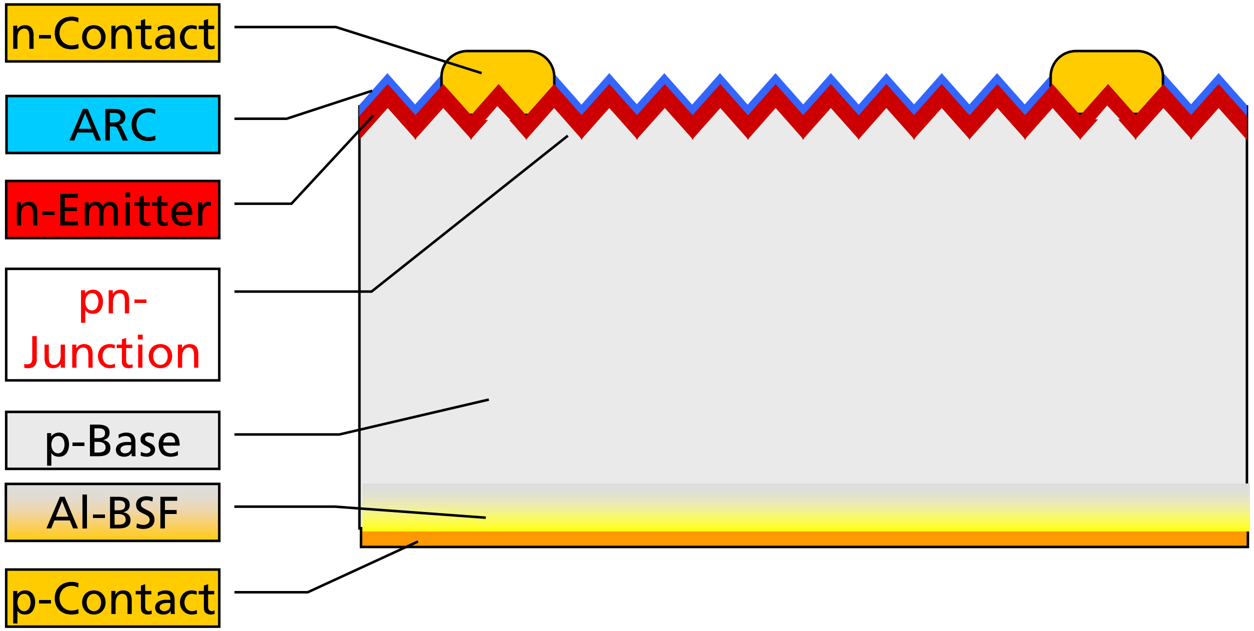
Bridgman Solidification



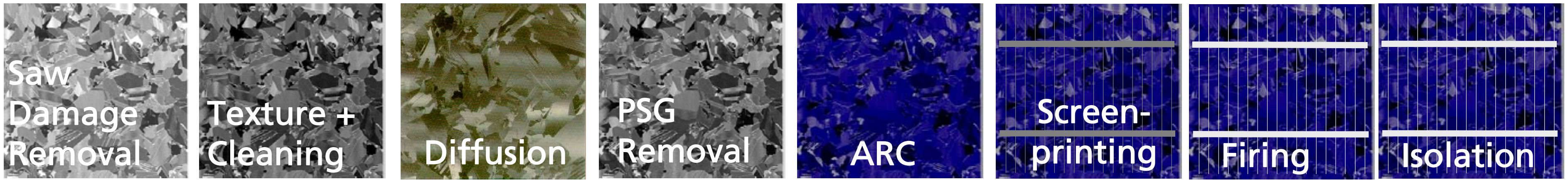
**Interesting further approaches: ribbon, sheet material, but: savings of scale?**

Sketches courtesy of W. Koch

# Si Cell technology – State of the Art in Industry

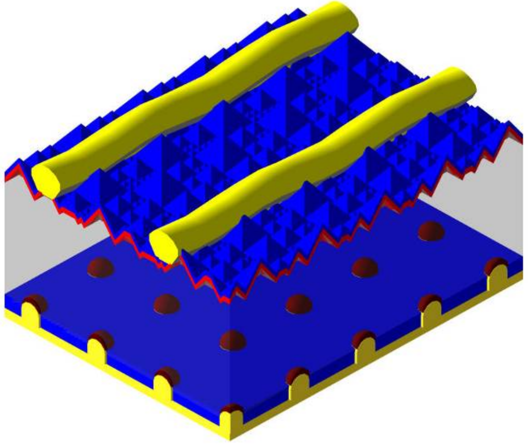



Process

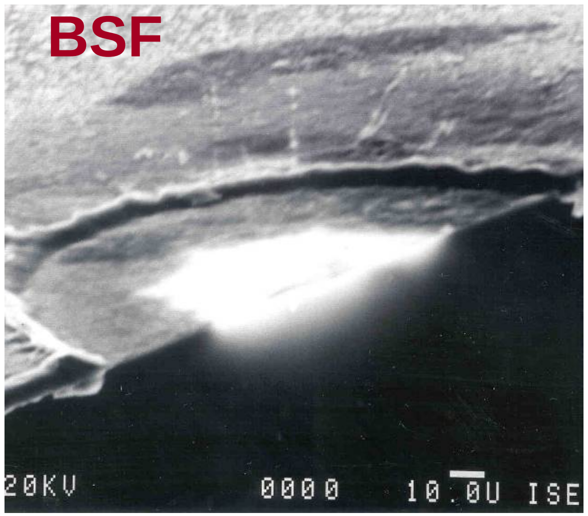


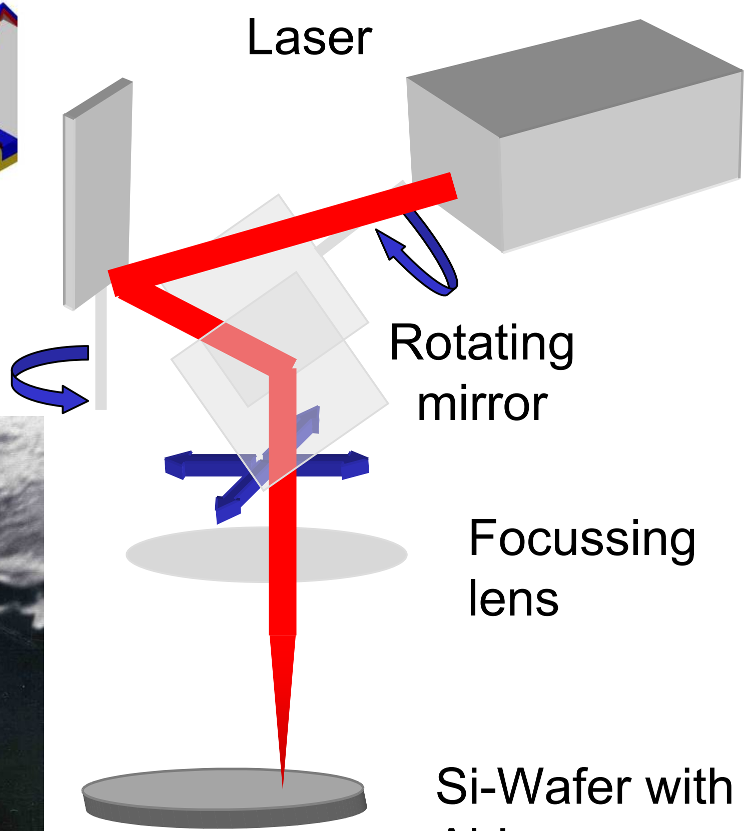

Graphics courtesy of S. Glunz

# Laser Fired Contacts



**LFC with local Al-BSF**

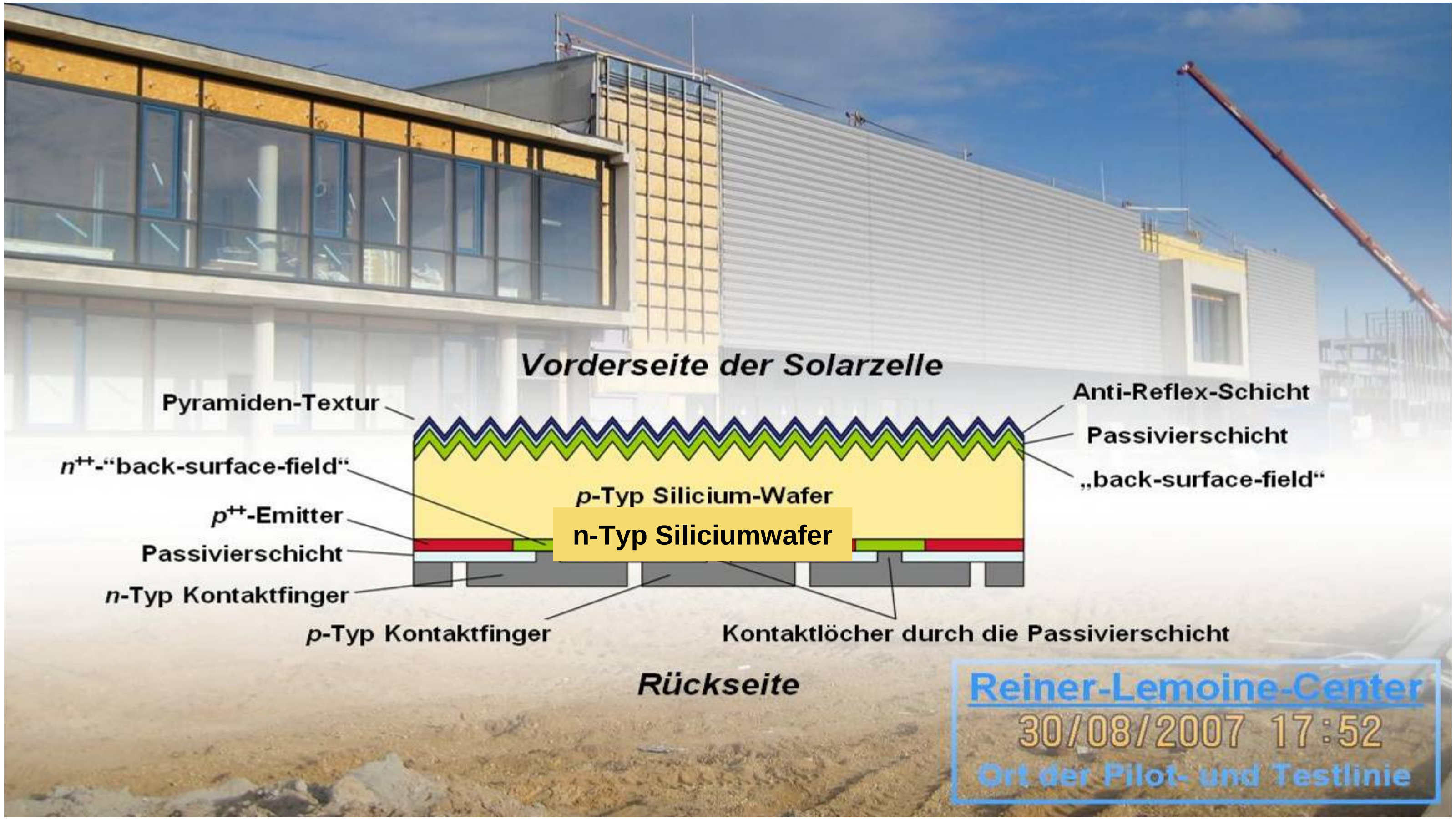



- Simple method to produce locally alloyed Al contacts
- On-the-fly processing with mirror scanners:
  > 10.000 contacts/s
- Contactless in-line process

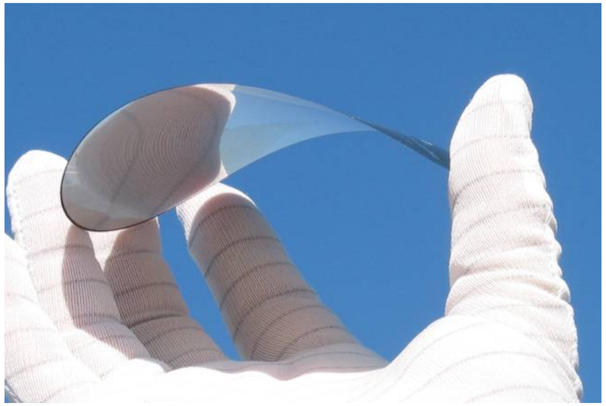
A. Grohe et al., in Proc. 21st EU-PVSEC, (Dresden 2006).

# High-Efficiency Back Contact Solar cells
## *using laser technology*




D. M. Huljić et al, in Proc. of the 21st EU PVSEC, (Dresden,2006).

# Thin Monocrystalline Silicon Solar Cells



**LFC cell concept yields very high efficiencies for thin cells**

- 20.2% on 36 µm thin 0.5 Ωcm Fz-Si
- 20.4% on 65 µm thin 0.1 Ωcm Fz-Si
- 19.5% on 36 µm thin 0.8 Ωcm Cz-Si

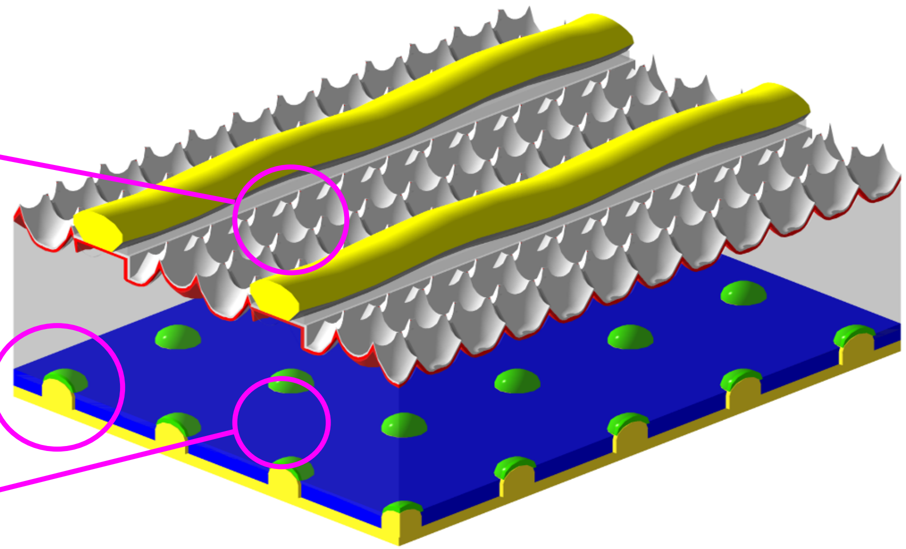
\+ Light-induced degradation in thin Cz-Si strongly reduced

# High-efficiency ISE solar cell structure for mc silicon

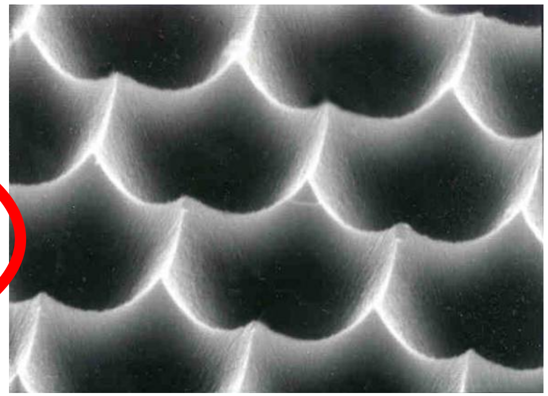
**Plasma-textured surface:**
Low reflection and good „light trapping“

**Laser-fired contacts (LFC):**
Low contact resistance and high voltage

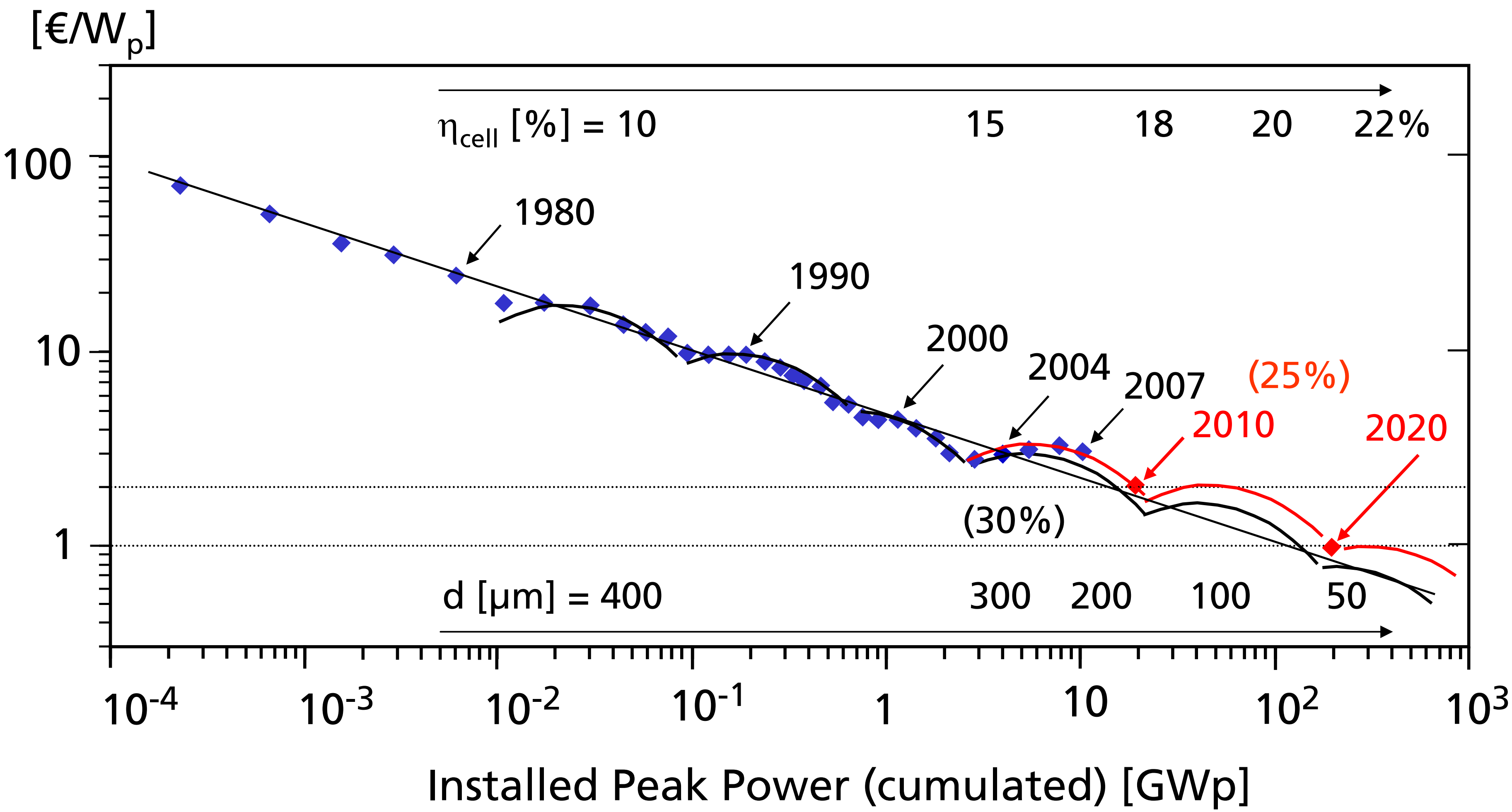
**Thermal oxide:**
Surface passivation and high internal reflectivity



**Wafer thickness: 99 µm**
Efficiency: 20.3% (1 $cm^2$)
*world record for mc-Si!*

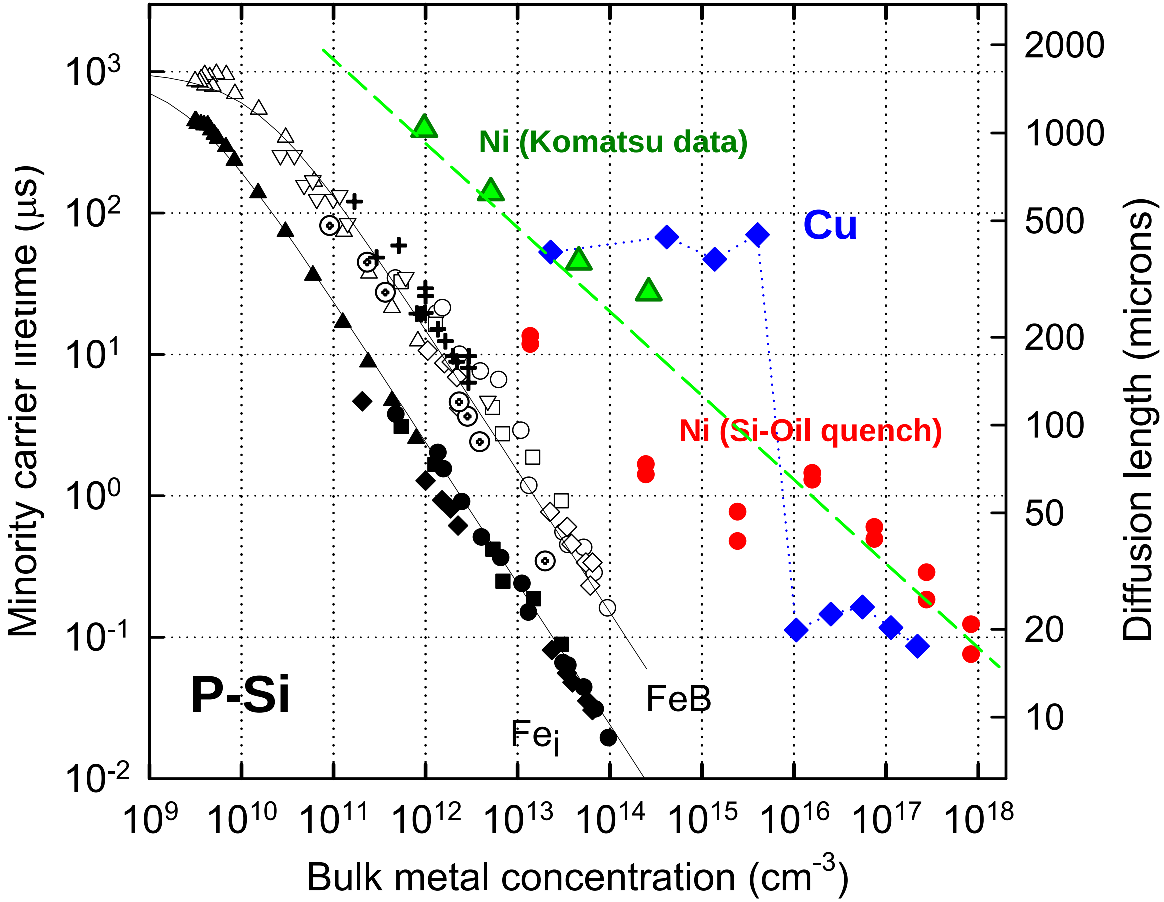


# Price learn curve of crystalline Si PV-modules



# Impact of Ni, Fe, and Cu on lifetime in p-Si

Electrical properties are very sensitive to small amounts of impurities.

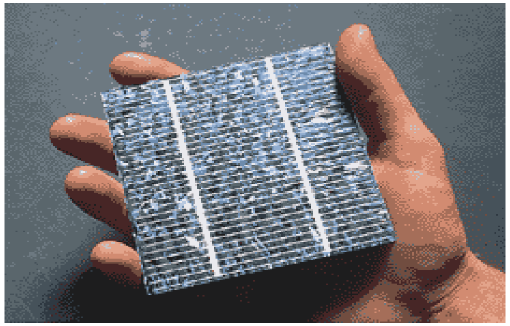



# Some PV cell materials were found by NAA analysis to have extraordinary large T-Metals concentrations

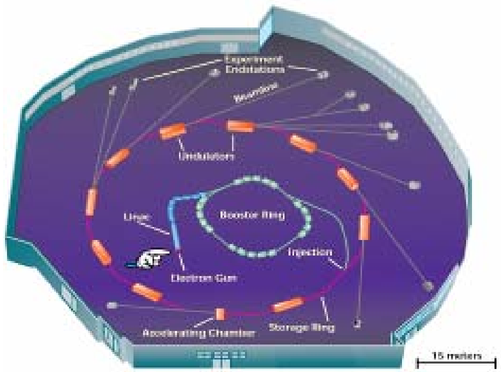
| Element | ASTROPOWER | BaySix | EFG |
|---|---|---|---|
| Fe | **1.50E+16** | **4.00E+14** | **6.00E+14** |
| Ni | **1.80E+15** | *less than DL (3e14)* | *less than DL (1.1e14)* |
| Co | **9.70E+13** | **2.10E+13** | **1.70E+12** |
| Cu | *less than DL (7.8e12)* | <2.4e14 | *<1.3e14* |
| Cr | **1.80E+15** | **1.00E+13** | **1.70E+12** |
| Hf | *less than DL (1.8e12)* | **7.80E+12** | *less than DL (6.8e11)* |
| Mo | **4.60E+13** | **1.50E+13** | **6.40E+12** |
| W | **2.00E+13** | *less than DL (2.2e11)* | *less than DL (8e10)* |
| Au | **4.80E+11** | **6.50E+10** | **2.00E+10** |
| As | **4.70E+13** | **3.40E+12** | *less than DL (9.3e10)* |
| Sb | **2.40E+14** | **1.70E+12** | **1.20E+11** |
| Ga | **2.50E+13** | *less than DL* | **9.00E+12** |

- If such a high concentration of metals were all electrically active, the efficiencies of multicrystalline solar cells would be far below 10%!
- As such material can achieve diffusion lengths between 20 and >250 microns, **the chemical state and spatial distribution of transition metals determines their electrical activity, rather than the metal concentration!**

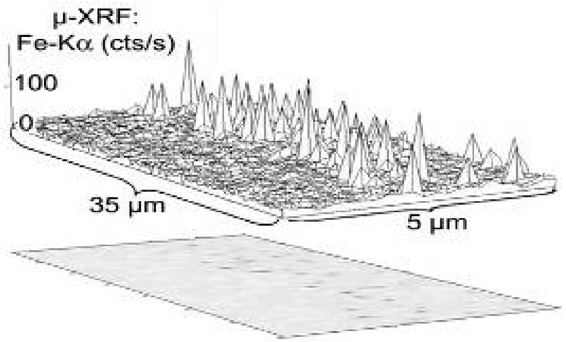
# Applications of synchrotron radiation for studies of metal impurities in silicon



Multicrystalline Silicon
Solar Cell

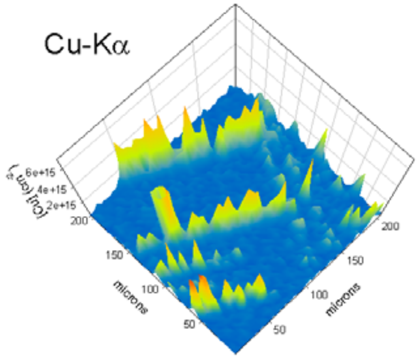



Advanced Light Source, Lawrence Berkeley Nat. Lab.

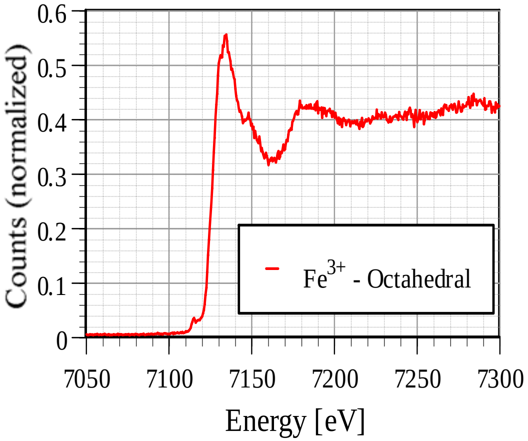



$FeSi_2$ distribution along grain
boundary in multicrystalline silicon
sheet material

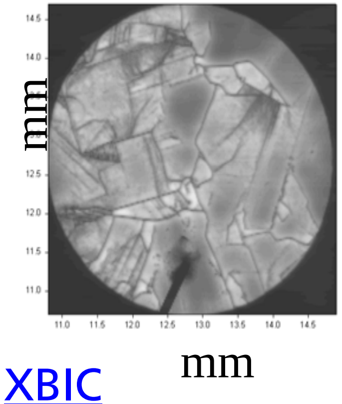
# Synchrotron x-ray techniques for the study of metals in mc-Si




μ-XRF
*(X-ray fluorescence microscopy)*:
Distribution, elemental composition, size, morphology of metal-rich nanoclusters.



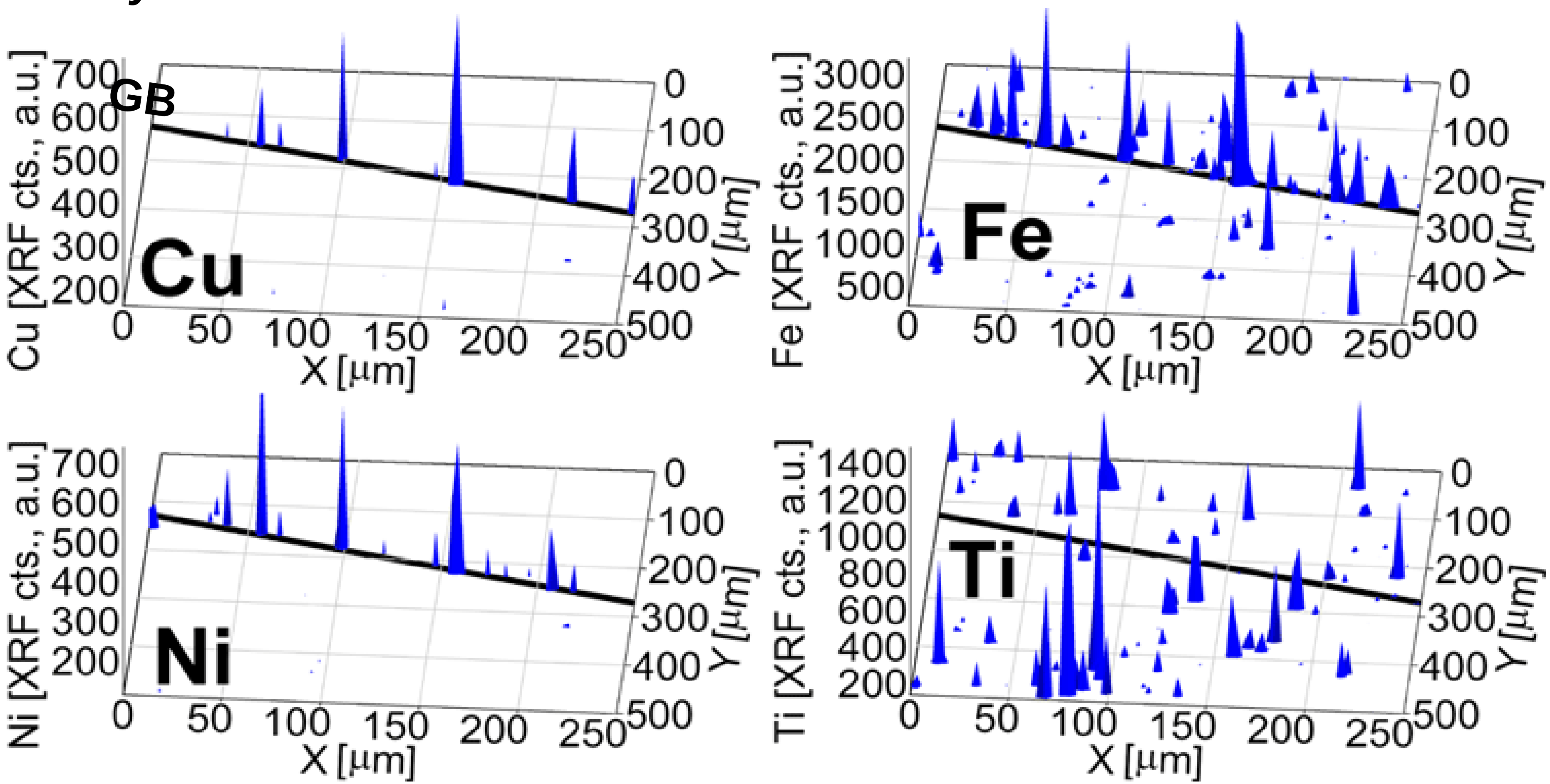

μ-XAS
*(X-ray absorption microspectroscopy)*:
Chemical state of metal-rich nanoclusters.




XBIC
*(X-ray beam induced current)*:
Maps underperforming regions, analogous to LBIC.

SR-XBIC
*(Spectrally-resolved XBIC)*:
Quantifies impact of metals on minority carrier diffusion length, analogous to SR-LBIC.

# Distribution of metal species depends on metal, process history

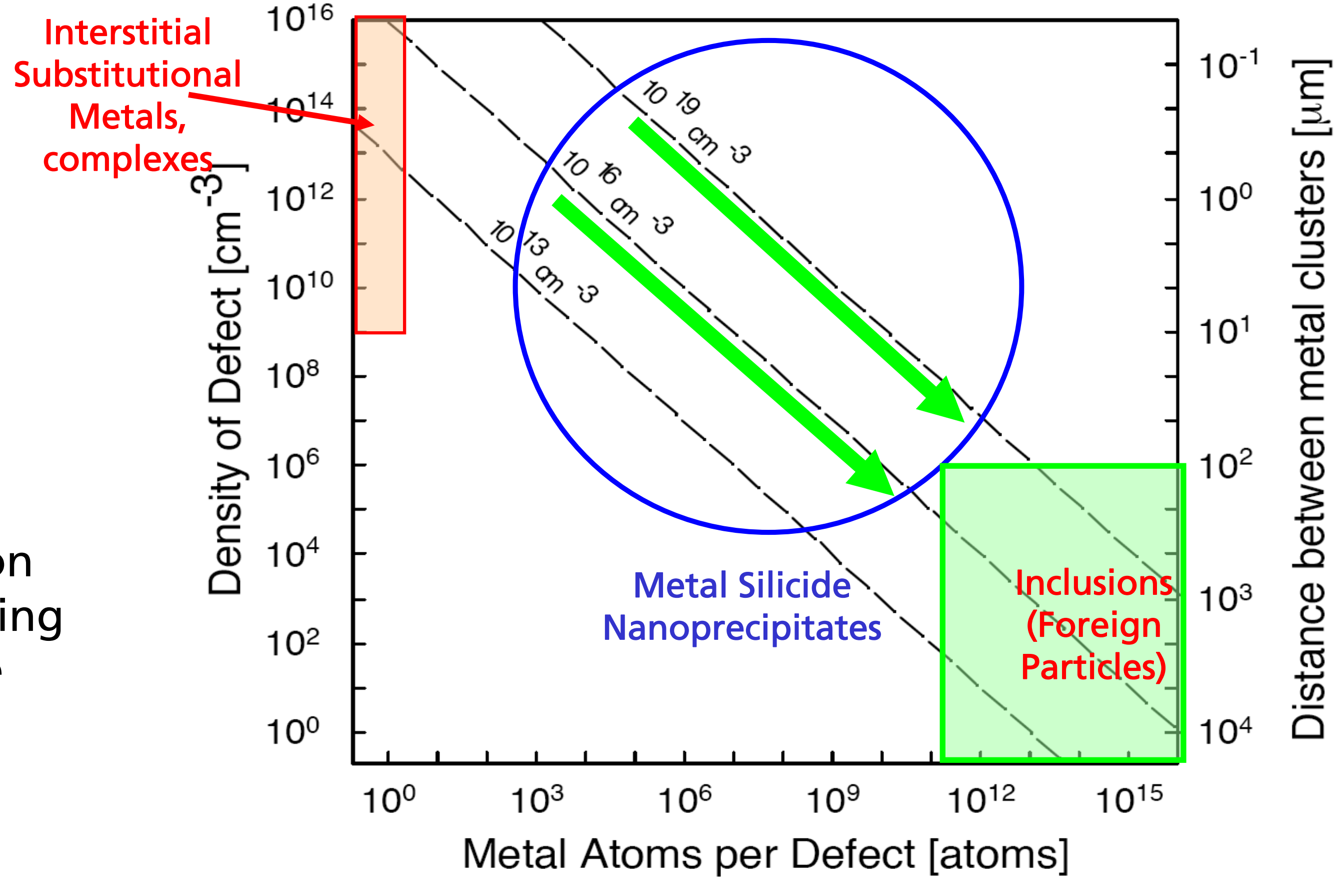



T.Buonassisi, A.A. Istratov et al.,Prog. Photovolt.: Res. Appl., 2006

# Goal of defect engineering of metal impurities

*Improvement through change in the state/distribution of metals*

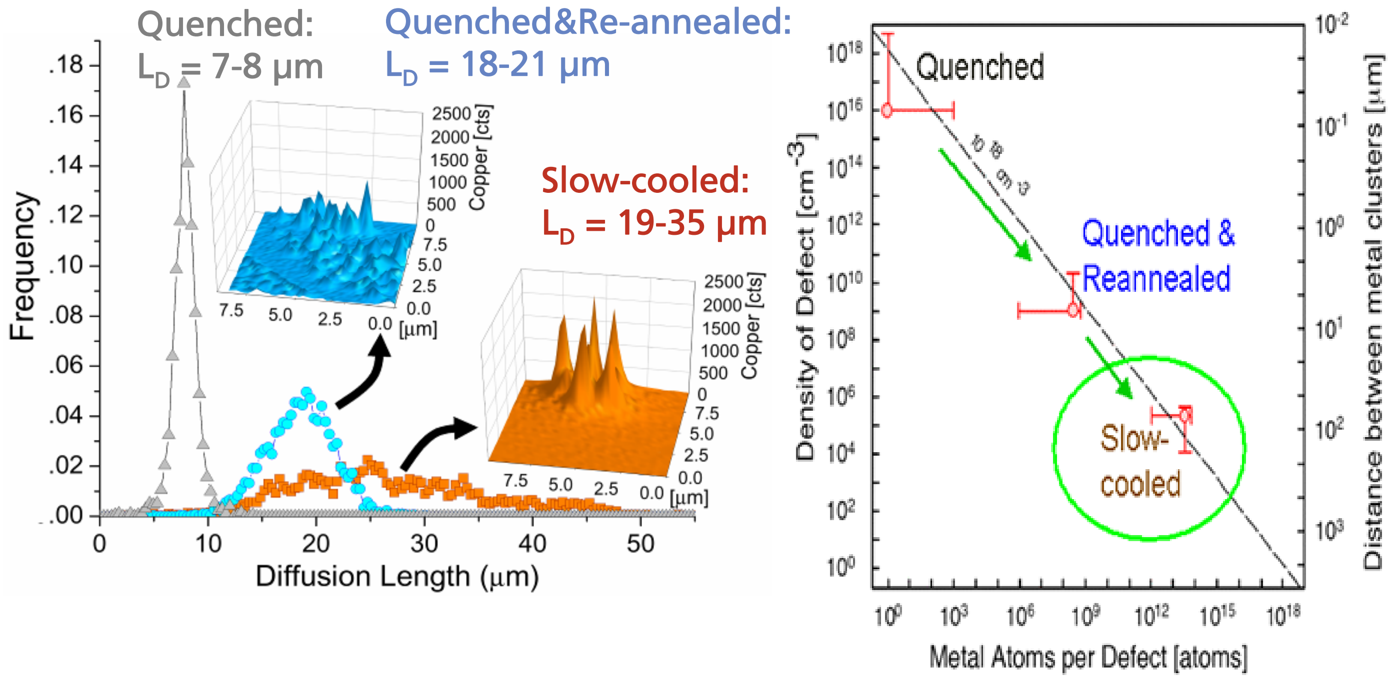
- Gettering improves material by removing metals from the device area.
- Defect engineering improves material by converting metals into their least recombination active state, while keeping the metals in the device area




T.Buonassisi, A.A.Istratov, M.A.Marcus, B.Lai, Z.Cai, S.M.Heald, E.R.Weber, Nature Materials, **4**, 676, (2005)

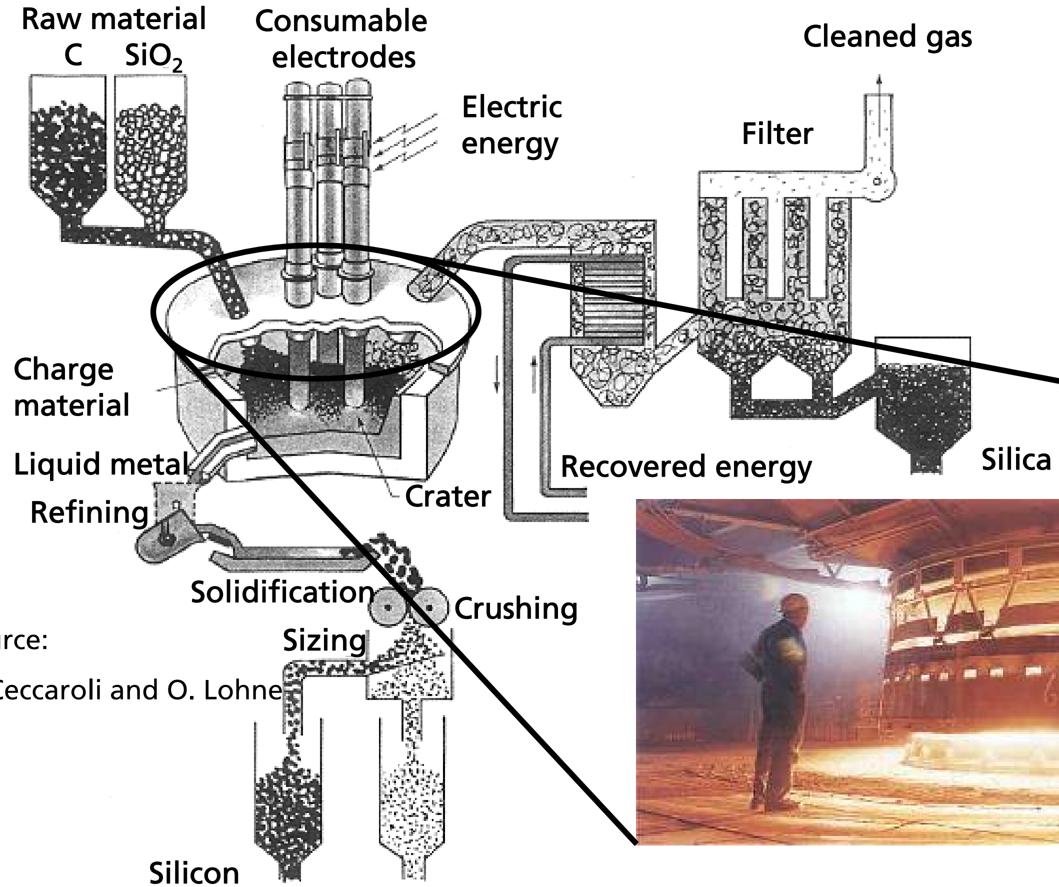
# Our studies showed that properly treated Si even with high metal content can have promising properties ('dirty Si')

mc-Si intentionally contaminated at 1200°C, either quenched in silicone oil, or quenched and then reannealed again at 655°C, or slowly cooled in the furnace.




T.Buonassisi, A.A.Istratov, M.A.Marcus, B.Lai, Z.Cai, S.M.Heald, E.R.Weber, Nature Materials, **4**, 676, (2005)

# From quartz to coal to metallurgical Silicon (mg-Si)




Source:

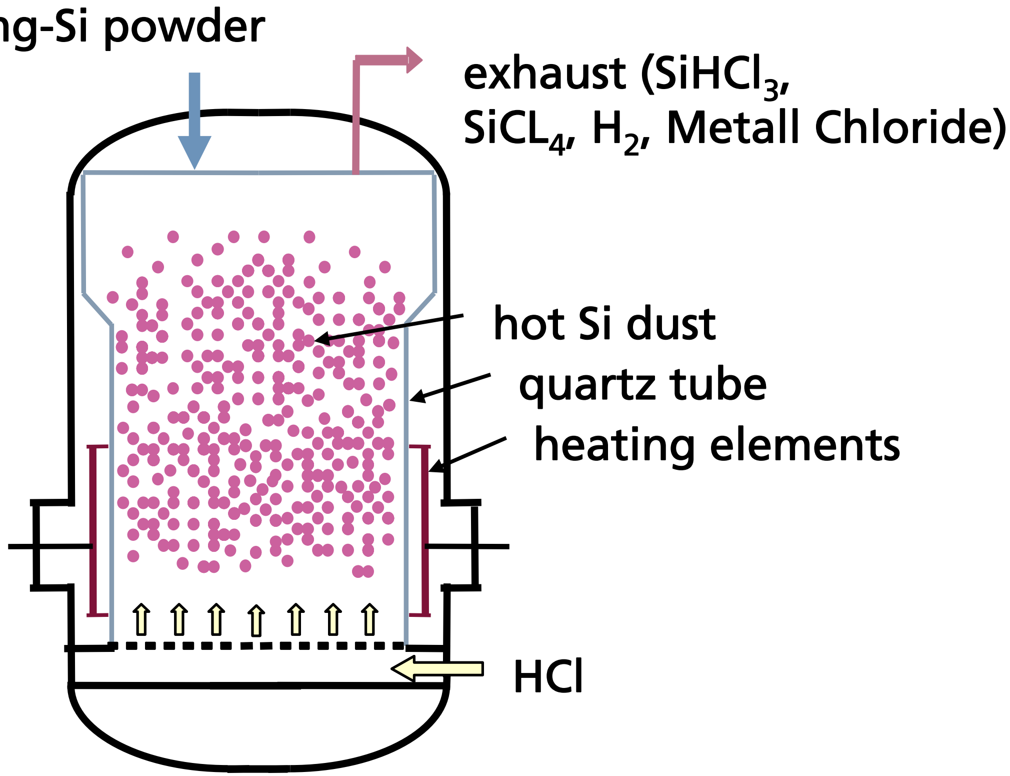
B. Ceccaroli and O. Lohne

Source: RW silicium

- 1 Mio t/a
- 1 \$/kg

Source: Elkem

# From mg-Si to ultrapure poly-Si: the Siemens Process

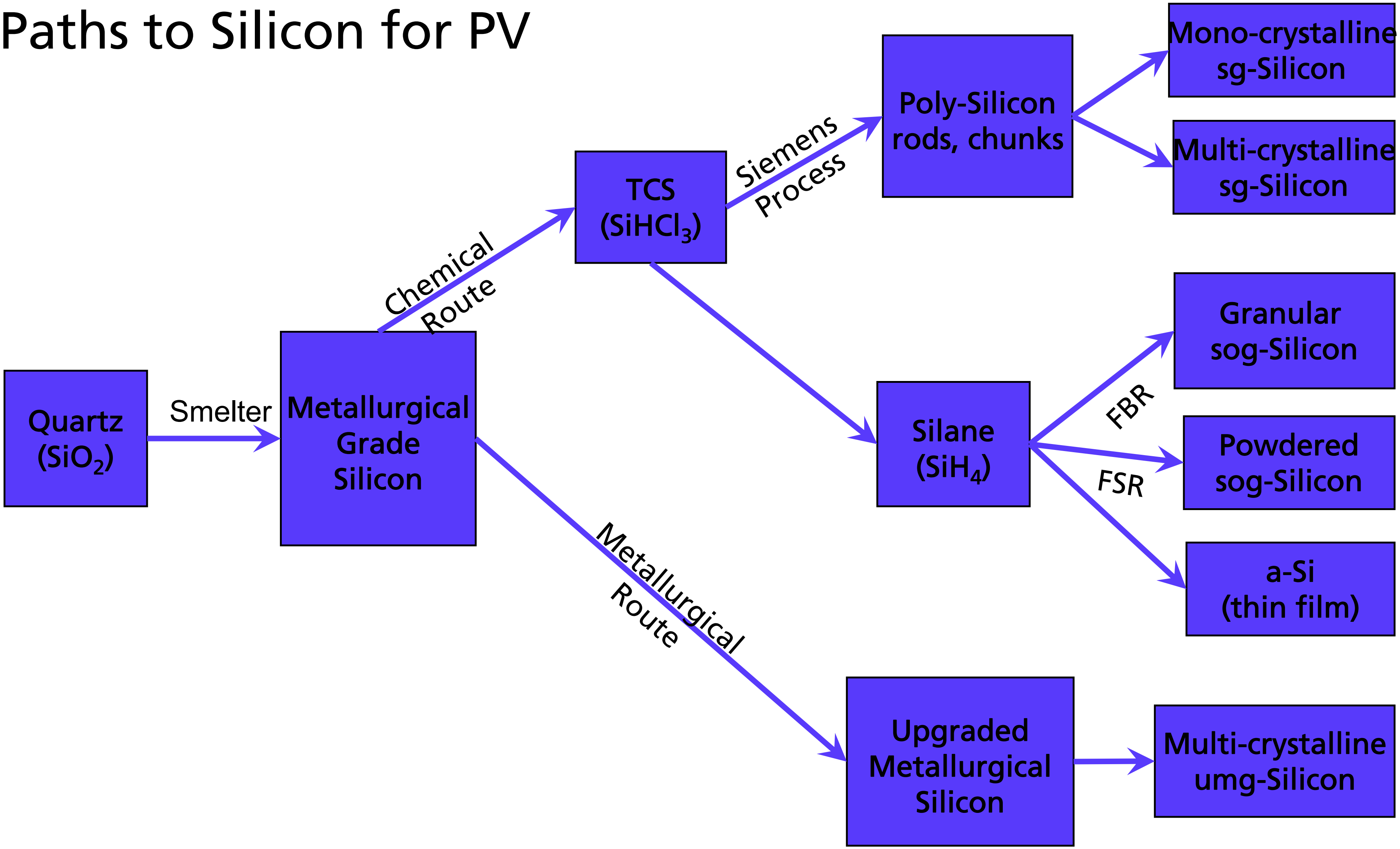



'fluidised bed' reactor


fractional distillation

Alternative Technology for PV: purified ('upgraded') metallurgical Si, umg-Si

# Paths to Silicon for PV




Slide design courtesy of M. Verschuur

# Silicon feedstock material

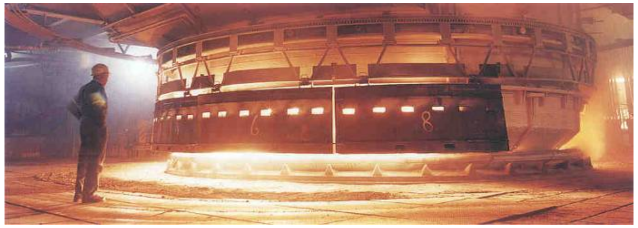
- Semiconductor-grade Si: Siemens process, Si distilled in gas phase;
  B, P: well controlled, metals in ppb and below range

- Solar-grade Si: purified via gas phase, simple crystallization;
  B, P: well controlled, other impurities around & below ppm range

- Upgraded metallurgical Si: Dopants reduced in liquid phase;
  B,P: reduced just as needed, other impurities in ppm range

- Metallurgical Si: 98% to 99.9% pure,
  metallic conductivity, impurities in several-ppm and more range

# Physicochemically purified feedstock: upgraded mg-Si



Source: Elkem

$SiO_2 + C \rightarrow Si + CO_2$

Typical throughput:

approx. 10.000 – 15.000 t/a mg-Si

Source: RW Silicium

Quartz $SiO_2$

Coal

Wood chips

→ Carbothermic reduction

mg-Si < 99,5%

2-3 times, Si in liquid or solid phase

- Ultrahigh temperatures (therm./plasma)
- Slag treatment
- …

Reduction dopants →

- Segregation
- Leaching

Reduction metals

→ umg-Si 99,999%

# Upgraded mg-Si: Pro's and Con's

**PRO's**

- Throughput of purification can be as high as mg-furnace: 10.000 – 15.000 t/a
- Less energy input per kg of purified silicon
- Less (chlorine) chemistry
- Lower investment cost
- ➢ Lower cost for purification

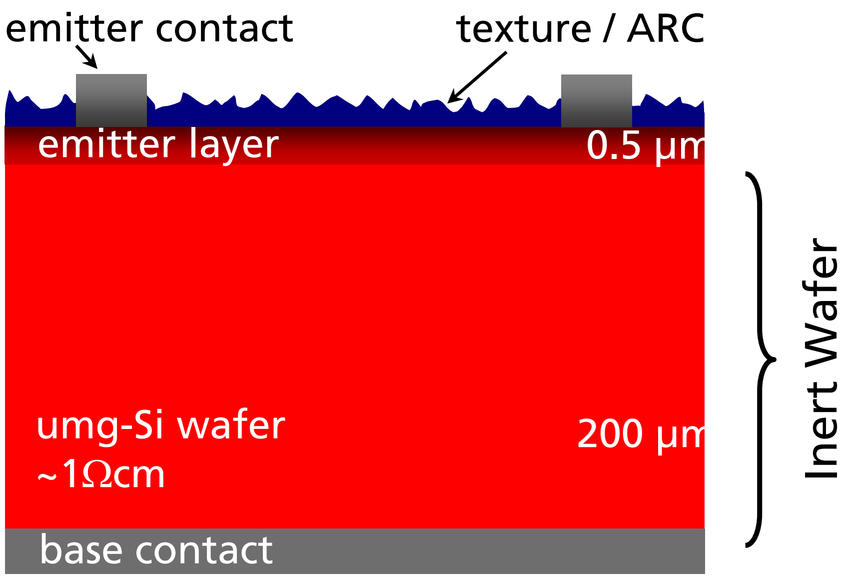
**CON's**

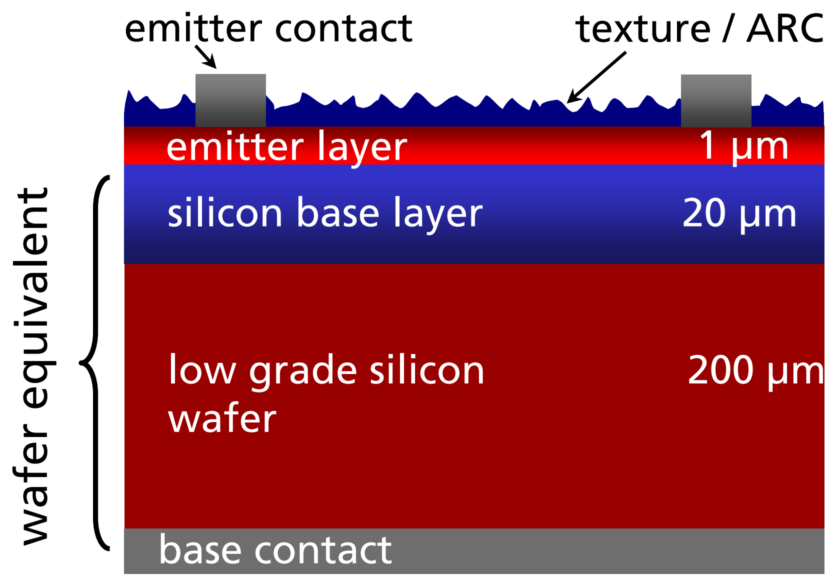
- Achievement of specifications for PV (still) difficult
- Quality control necessary (but difficult)

# Concepts worked on at ISE: InertCell, EpiCell

InertCell: Wafer solar cell made from (moderately) purified silicon, impurities inactivated

EpiCell: Epitaxial silicon thin-film solar cell on (near) metallurgical grade mc-Si wafer substrate

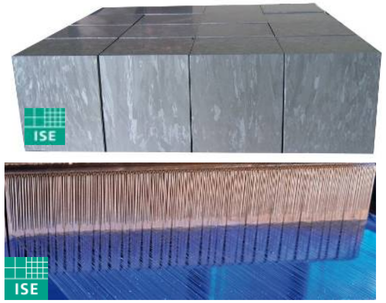
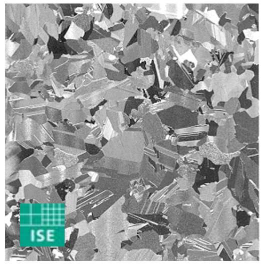
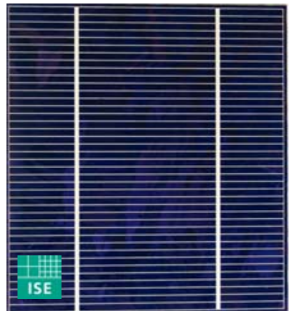


# Upgraded metallurgical Si for PV: materials challenges

- Crystallization: Dopant segregation, conduction type reversal
- Wafering: sawing problems due to SiN, SiC inclusions
- Cell processing: has to take into account high metal content, dangers of shunts, lifetime degradation, breakdown voltage reduction

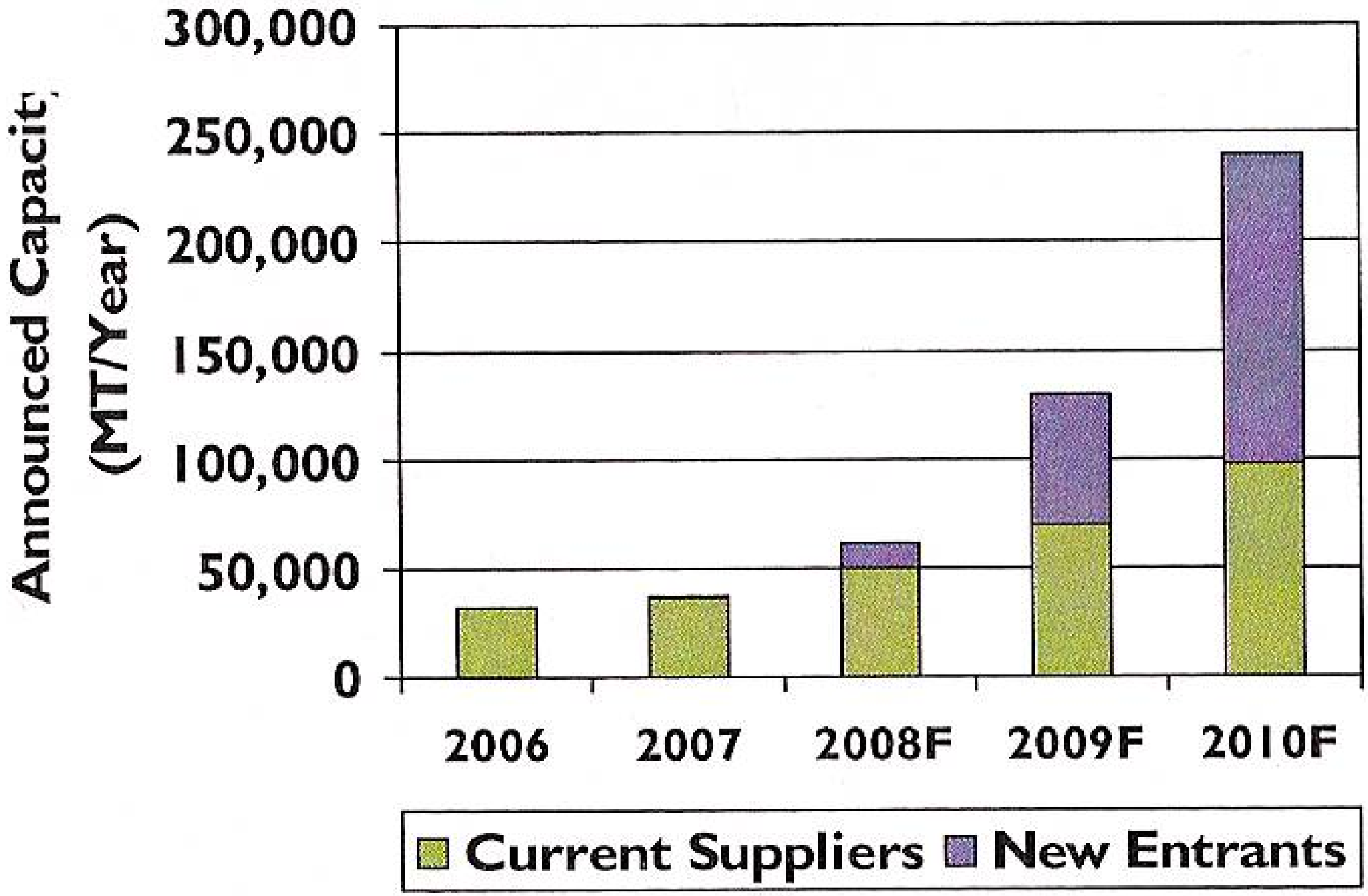


**Silicon feedstock** → **Crystallization** → **Block shaping Wire sawing** → **Separation/ Cleaning** → **solar cell process**

Graphics courtesy of S. Reber

# Polysilicon Capacity Trends:
## *How will new entrants fair?*




Includes captive and merchant markets; solar and semiconductor applications.

Source: SEMI, June 2008

# Segmentation of the PV Market

- 1 - 5 %: Organic, Dye, Nanostructure Cells
- 6 - 11%: Thin film cells (a-Si, microcryst.-Si, CIS, CIGS, CdTe)
- 14 - 18%: mc-Si, umg-Si, simple c-Si cells
- 20 - 24%: High efficiency, mainly c-Si cells
- 36 - 41.1%: High-efficiency III/V tandem cells for concentrators with 25 - 28% module efficiency

New world record (390x), ISE January 2009!

# Conclusion: the big picture for photovoltaics

- PV will grow in the coming decades 10 - 100 times in market volume, from a $15 B market into a $100 - 300 B market, replacing fossil fuels, reducing climate gases, and providing unlimited energy.
- Crystalline Silicon will continue to dominate the rapidly growing PV market, thin film modules out of a-Si, CIS, or CdTe today have an interesting market, long-term success depends on efficiency gains and further cost reduction, high efficiency CPV will enter the market soon.
- Organic solar cells, other ‘3rd generation’ concepts will serve interesting market niches, but are not likely to affect the global energy picture.
- One key to decreasing costs for PV is the global production volume; effective support mechanisms such as attractive feed-in rates are still necessary.
- The change from semiconductor-grade (Siemens-process) to solar-grade and then to upgraded metallurgical Si with higher impurity content, employing gettering and defect engineering, opens new ways for volume growth of Si-PV.

My final message:

– C – - Life

– Si – - Energy